

Helsinki 4.8.2004

E T U O I K E U S T O D I S T U S  
P R I O R I T Y   D O C U M E N T



Hakija  
Applicant

CTT Cancer Targeting Technologies Oy  
Helsinki

REC'D 24 SEP 2004

WIPO PCT

Patentihakemus nro  
Patent application no

20030923

Tekemispäivä  
Filing date

19.06.2003

Kansainvälinen luokka  
International class

C07K

Keksinnön nimitys  
Title of invention

"Inhibitors of the leukocyte proMMP9/beta2 integrin complex"  
(Leukosyntti-proMMP-9/beta2-integriinin kompleksin inhibiittorit)

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Osoite: Arkadiankatu 6 A Puhelin: 09 6939 500 Telefax: 09 6939 5328  
P.O.Box 1160 Telephone: + 358 9 6939 500 Telefax: + 358 9 6939 5328  
FIN-00101 Helsinki, FINLAND

## Inhibitors of the leukocyte proMMP9/ $\beta_2$ integrin complex

### INTRODUCTION

5 The leukocyte integrin family consists of four heterodimeric glycoproteins with specific  $\alpha$ -chains ( $\alpha_L$ ,  $\alpha_M$ ,  $\alpha_X$ , or  $\alpha_D$ ) and a common  $\beta_2$ -chain (CD18). They play an essential role in mediating adhesion of cells in the immune system (1). The major ligand-binding site locates to an 200 amino acid long sequence within the  $\alpha$ -chain called I or inserted domain, which is homologous to the A domains of von Willebrand factor, repeats of cartilage matrix protein and collagen (2).

10 Among the  $\beta_2$  integrins,  $\alpha_M\beta_2$  is the most promiscuous binder being able to interact with a multitude of unrelated ligands. These include ICAM 1 to 5, complement fragment iC3b, fibrinogen, uPAR, E-selectin and various extracellular matrix proteins  
15 (see (3) and references therein). The integrin has also been shown to have a capacity to bind certain enzymes, but whether this is important for leukocyte adhesion or immune reactions is unclear. Such enzymes showing integrin-binding activity are catalase (4), myeloperoxidase (5) and the proteinases elastase (6) and urokinase (7).

20 Extensive work has been done to identify the ligand binding sites in  $\beta_2$  integrin I domains, but less is known about the interacting ligand regions (8,9). Recently, the structure of an  $\alpha_L$  I domain/ICAM-1 complex was reported (10). Low molecular weight peptides binding to the  $\beta_2$  integrins are useful reagents to study integrin function, and such peptides have been derived from ICAM-2 (11), fibrinogen (12),  
25 and Cyr61 (13). We have used phage display libraries to study the peptide binding specificity of integrins and to develop potential drug leads. In our previous study, we isolated the biscyclic peptide CPCFLLGCC (LLG-C4)<sup>1</sup> as the most active binder to the purified  $\alpha_M\beta_2$  integrin (14). Leukocytes can efficiently adhere to the immobilized LLG-C4 peptide via the  $\alpha_M\beta_2$  and  $\alpha_X\beta_2$  integrins.

30

We have now extended phage display screenings to the purified  $\alpha_M$  I domain. This has resulted in the identification of a novel I domain-binding tetrapeptide motif D/E-

D/E-G/L-W, which is found on some of the known  $\beta_2$  integrin ligands and interestingly also on the catalytic domain of MMPs. We show that the D/E-D/E-G/L-W motif mediates binding between an MMP and  $\beta_2$  integrin, and proMMP-9 gelatinase, the major MMP of leukocytes (15-18), occurs in complex with the  $\alpha_M\beta_2$  5 and  $\alpha_L\beta_2$  integrins in leukemic cell lines following cellular activation. The peptide inhibitors of the integrin-MMP complex prevent leukaemia cell migration, suggesting a role for the complex in cell motility.

## EXPERIMENTAL PROCEDURES

10

### Antibodies and Reagents

The antibodies MEM170 and LM2/1 were against the  $\alpha_M$  and the MEM-83 and TS2/4 antibodies against the  $\alpha_L$  integrin subunit (19,20). The monoclonal antibody 7E4 (21) reacted with the common  $\beta_2$ -chain of the leukocyte integrins. The  $\alpha_M$  antibody

15 OKM10 was obtained from the American Type Culture Collection, ATCC, Rockville, MD (22). A monoclonal antibody against ICAM-5 (TL3) (23) was used as an antibody control. The monoclonal anti-MMP-9 antibody (GE-213) and anti-MMP-2 antibody (Ab-3) were obtained from Lab Vision Corporation (Fremont CA) and from Oncogene<sup>TM</sup> research products, respectively. Affinity purified rabbit anti-MMP-9

20 polyclonal antibodies were from the Borregaard laboratory (24). The rabbit anti-mouse horseradish peroxidase-conjugated secondary antibody was from Dakopatts a/s (Copenhagen, Denmark). Inh1 (2R-2-(4-biphenylylsulfonyl)amino-N-hydroxy propionamide) was purchased from Calbiochem, La Jolla, CA. Human recombinant ICAM-1 was obtained commercially by R&D systems (Minneapolis, MN). ICAM-1-

25 Fc fusion protein was expressed in chinese hamster ovary cells and purified as described (14). The synthetic peptides CTT, STT, LLG-C4 and RGD-4C were obtained as previously described (14,25). W→A CTT was ordered from Neosystem, Strasbourg, France. ProMMP-2 and proMMP-9 were obtained commercially (Roche).

In zymography, the commercial proMMP-9 showed the 92kDa monomer, 200 kDa 30 homodimer, and 120 kDa NGAL complex bands. The integrins  $\alpha_1\beta_1$  and  $\alpha_3\beta_1$  were purchased from Chemicon International (Temecula, CA). Human plasma fibrinogen and lovastatin were from Calbiochem.

### Phage display

Phage display selections were made using a pool of random peptides CX<sub>7-10</sub>C and X<sub>9-10</sub>, where C is a cysteine and X is any amino acid (14,25). Briefly,  $\alpha_M$  I domain-GST or GST fusion protein was immobilized on microtiter wells at 20  $\mu$ g/ml concentrations and the wells were blocked with BSA. The phage library pool was first subtracted on wells coated with GST and then unbound phage was transferred to  $\alpha_M$  I domain-GST-coated wells in 50 mM Hepes/5 mM CaCl<sub>2</sub>/1  $\mu$ M ZnCl<sub>2</sub>/150 mM NaCl/2% BSA (pH 7.5). After three rounds of subtraction and selection, individual phage clones were tested for binding specificity and the sequences of the phage that specifically bound to the I domain were determined (14).

### Peptide biosynthesis and chemical synthesis

The phage peptides were initially prepared biosynthetically as intein fusions. The DNA sequences encoding the peptides were PCR cloned from 1  $\mu$ l aliquots of the phage-containing bacterial colonies that were stored at -20°C. The forward primer was 5'-CCTTCTGCTCTCCAACGCCGACGGGGCT-3' and the reverse primer 5'-ACTTCAACCTGCAGTTACCCAGCGGCC-3'. The PCR conditions included initial denaturation at 94°C for 2 min followed by 30 cycles of 94°C 30 sec, 55°C 30 sec, and 72°C 30 sec. The PCR products were purified using QIAGEN Nucleotide removal kit. They were then digested with SapI and PstI restriction enzymes and ligated to a similarly digested and phosphatase treated pTWIN vector (New England Biolabs). Correct insertions were verified by DNA sequencing. Intein fusion proteins were produced in *E. coli* strain ER2566 and affinity purified on a chitin column essentially as described (26). The peptide was cleaved on the column, eluted and finally purified by HPLC. Chemical peptide synthesis was done using Fmoc-chemistry as described and the sequences were verified by mass spectroscopy (26).

### Phage binding assay

Phage ( $10^8$  infective particles/well) in 50 mM Hepes/5 mM CaCl<sub>2</sub>/1  $\mu$ M ZnCl<sub>2</sub>/0.5% BSA (pH 7.5) were added to microtiter wells coated with I domain-GST fusion or GST (20 ng/well). The phages were allowed to bind in the absence or presence of a competitor peptide (15  $\mu$ M) for one hour followed by washings with PBS containing

0.05% Tween 20. The bound phage was detected using 1:3000 dilution of a peroxidase-labelled monoclonal anti-phage antibody (Amersham Biosciences) and o-phenylenediamine dihydrochloride as a substrate. The reactions were stopped by addition of 10% H<sub>2</sub>SO<sub>4</sub> and the absorbance was read at 492 nm using a microplate reader.

5

### Pepspot

The peptides were synthesized on cellulose membranes as described (27). The membrane was blocked with 3% BSA in TBS containing 0.05% Tween 20, and 10 incubated with 0.5-5 µg/ml α<sub>M</sub> I domain for 2 h at room temperature. The DDGW peptide was used as a competitor at a 50 µM concentration. Bound α<sub>M</sub> I domain was detected using the monoclonal antibody LM2/1 (1 µg/ml) or MEM-170 (5 µg/ml) and peroxidase-conjugated rabbit anti-mouse antibody (1:5000 dilution) followed by chemiluminescence detection.

15

### Cell culture

The human HT1080 fibrosarcoma and THP-1 and Jurkat leukemic lines were obtained from ATCC and maintained as described previously (20, 25, 28). OCI/AML-3, derived from the primary blasts of an AML patient (29) was maintained in 10% 20 FBS/RPMI supplemented with L-glutamine, penicillin and streptomycin. Cell viability was assessed with a MTT (3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyl tetrazolium bromide) assay according to the instructions of the manufacturer (Roche).

30

### Purification of integrins

α<sub>L</sub>β<sub>2</sub> (CD11a/CD18, LFA-1), α<sub>M</sub>β<sub>2</sub> (CD11b/CD18, Mac-1) and α<sub>X</sub>β<sub>2</sub> (CD11c/CD18) integrins were purified from human blood buffy coat cell lysates by adsorption to the anti-CD11a (TS 2/4), anti-CD11b (MEM170), or anti-CD11c (3.9) antibodies linked to protein A-Sepharose CL 4B. The integrins were eluted at pH 11.5 in the presence of 2 mM MgCl<sub>2</sub>, and 1% n-octyl glucoside as described previously (28).

30

### Expression and purification of GST fusion proteins

The α<sub>L</sub>, α<sub>M</sub>, and α<sub>X</sub> I-domains were produced as GST fusion proteins in *E. coli* strains BL 21 or JM109 and purified by affinity chromatography on glutathione-coupled

beads (30, 31). GST containing CTT in the C-terminus was constructed using the protocols described for LLG-C4-GST (14) and glutathione-coupled beads were employed for purification. The purity of the GST-fusion proteins was confirmed by SDS-PAGE with Coomassie Blue staining and Western blot analysis. For pepspot  
5 analysis, GST was cleaved from the  $\alpha_M$  I domain with thrombin.

### Binding of MMPs to purified integrins

The purified I domains (GST- $\alpha_M$ , GST- $\alpha_L$ , GST- $\alpha_X$ ), or integrins ( $\alpha_M\beta_2$ ,  $\alpha_L\beta_2$ ,  $\alpha_X\beta_2$ ,  $\alpha_1\beta_1$ ) (1  $\mu$ g/well) were immobilized in 20 mM Tris, 150 mM NaCl, 1 mM CaCl<sub>2</sub>, 1  
10 mM MgCl<sub>2</sub>, and 1 mM MnCl<sub>2</sub>, pH 7.4. The wells were washed with PBST (10 mM phosphate, 140 mM NaCl, pH 7.4, containing 0.05% Tween20) and blocked with 3% BSA in PBST. ProMMP-2, proMMP-9, or the p-aminophenyl mercuric acetate (APMA) or trypsin-activated forms (32) were incubated for 2 h at room temperature.  
15 In the inhibition experiments, CTT and Inh1 were first preincubated with the proMMPs for 30 minutes at room temperature. The wells were washed three times and incubated with anti-MMP-9 (GE-213) or anti-MMP-2 (Ab-3) antibody at a 2  $\mu$ g/ml concentration in PBST for 1 h. Bound antibodies were detected using peroxidase-conjugated rabbit anti-mouse IgG (DAKO, Glostrup, Denmark) and o-phenylenediamine dihydrochloride as a substrate.

20

### Coprecipitation of $\beta_2$ integrin and progelatinases

Serum-free conditioned medium containing proMMP-2 and proMMP-9 was collected from human HT-1080 fibrosarcoma cells grown in the presence of 100 nM phorbol ester 4 $\beta$ -Phorbol 12,13-dibutyrate (PDBu) (Sigma-Aldrich, St. Louis, MO) overnight  
25 at +37°C. A 500  $\mu$ l volume of the supernatant was incubated with 100 ng of GST- $\alpha_M$ , GST- $\alpha_L$ , or GST- $\alpha_X$  I-domain or  $\alpha_M\beta_2$  integrin for 3 h at 25°C. GST and GST-LLG-C4 were used to determine non-specific binding. CTT, STT, LLG-C4, and ICAM-1 were used as competitors at a 200  $\mu$ g/ml concentration, and the antibodies LM2/1 and TL3 at 40  $\mu$ g/ml. After an hour incubation at +4°C, complexes of I-domain and  
30 gelatinases were pelleted with Glutathione Sepharose. Integrin complexes were captured by incubating first with the OKM10 antibody for 3 h at +4°C and then with protein G Sepharose for 1 h. After centrifugation and washing, samples were analyzed

by gelatin zymography on 8% SDS-polyacrylamide gels containing 0.2 % gelatin (32).

#### **Effect of peptides on proMMP-9 release from cells**

5 THP-1 cells (40 000/100 µl) were incubated in serum-free RPMI medium for 48 h in the absence or presence of 200 µM peptide as described in the text. Aliquots of the conditioned media were analyzed by gelatin zymography.

#### **Interaction between CTT and proMMP-9**

10 CTT-GST and GST control (5 µg/well) were coated overnight on 96-well microtiter plates in 50 µl TBS followed by blocking of the wells by BSA. proMMP-9 or APMA-activated form (80 ng/well) was incubated in the absence or presence of competitors for 2 h in 50 µM Hepes buffer containing 1 % BSA, 5 mM CaCl<sub>2</sub>, and 1 µM ZnCl<sub>2</sub> (pH 7.5). After washing, bound MMP-9 was determined with anti-MMP-9 and HRP-conjugated anti-mouse IgG as described above. To examine complexing of CTT with proMMP-9 in cell culture, THP-1 cells were activated with PDBu for 30 min and then incubated with CTT, W→A CTT, or Inh1 (each 200 µM) at +37°C in serum-free medium. Samples were taken from the media at 0, 1, 2, 3, 4, and 5 h time points and analyzed by zymography and Western blotting with polyclonal anti-MMP-9 antibodies. Experiments with HT-1080 cells were performed similarly except that the medium samples were collected after 6 h.

#### **Cell surface labelling, immunoprecipitation and immunoblotting**

Non-activated or PDBu-activated THP-1 cells ( $1 \times 10^7$ ) were subjected to surface labelling using periodate tritiated sodium borohydride (33). The [<sup>3</sup>H]-labelled cells were lysed with 1% (v/v) Triton X-100 in PBS, clarified by centrifugation and precleared with protein G-Sepharose. The lysate was immunoprecipitated with polyclonal anti-MMP-9, α<sub>M</sub> (OKM-10) or β<sub>2</sub> (7E4) antibodies. After an hour incubation at +4°C together with protein G-Sepharose, immunocomplexes were pelleted, washed and resolved on 8-16% SDS-PAGE gels (Bio-Rad, Hercules CA). The gels were treated with an enhancer (Amplify, Amersham Biosciences), dried and exposed. Non-labelled THP-1 cells ( $1 \times 10^7$ ) were similarly lysed and immunoprecipitated as above. The samples were resolved on 4-15% SDS-PAGE gels

and transferred to nitrocellulose membranes. Immunodetection was performed with  $\alpha_M$  (MEM170) antibody (10  $\mu$ g/ml) followed by peroxidase-conjugated anti-mouse IgG and chemiluminescence detection (Amersham Biosciences). The membranes were stripped of bound antibodies and reprobed with monoclonal  $\alpha_L$  chain (TS2/4) or 5 polyclonal anti-MMP-9 antibodies.

### **Immunofluorescence**

Immunofluorescence was performed on resting cells or the cells activated with PDBu for 30 min. A portion of the cells was treated with ICAM-1 or CTT to block  $\beta_2$  10 integrins or gelatinases, respectively. Cells were bound to poly-L-Lysine coated cover slips, fixed with methanol for 10 min at -20°C or with 4% paraformaldehyde for 15 min at +4°C, and permeabilized with 0.1% Triton X-100 in PBS at room temperature for 10 min followed by several washings. The cover slips were incubated with rabbit anti-MMP-9 polyclonal and mouse anti- $\alpha_M$  (OKM-10) antibodies diluted 1:500. After 15 washing with PBS, the secondary antibodies, rhodamine (TRITC)-conjugated porcine anti-rabbit or FITC-conjugated goat anti-mouse (Fab')<sub>2</sub> (Dakopatts a/s, Copenhagen, Denmark) were incubated at a 1:1000 dilution for 30 min at room temperature. The samples were mounted with moviol, incubated in the dark for 2 days, and examined by a confocal microscope (Leica multi band confocal imagine spectrophotometer) at a 20 400x magnification or a fluorescence microscope (Olympus Provis 70) at a 60x magnification.

### **Cell adhesion and migration**

Fibrinogen and ICAM-1-Fc were coated at 40  $\mu$ g/ml in TBS at +4°C. Peptides (2 25  $\mu$ g/well) were coated in TBS containing 0.25% glutaraldehyde at +37°C. The wells were blocked with 1% BSA in PBS. THP-1 cells (50 000/well) with or without PDBu activation were added in 0.1% BSA-RPMI medium in the presence or absence of 200  $\mu$ M peptides or monoclonal antibodies at 50  $\mu$ g/ml. After 30-35 minutes the wells were washed with PBS to remove non-adherent cells and the adhesive cells were 30 quantitated by a phosphatase assay. The cell migration assay was conducted using transwell migration chambers (8  $\mu$ m pore size, Costar) in serum-containing medium as described (14). Briefly, the membranes were coated on the upper and lower surface with 40  $\mu$ g/ml GST, LLG-C4-GST, or left uncoated. The wells were blocked with

10% serum-containing medium for 2 h. THP-1 cells (50 000/100 µl) or HT1080 (20  
000/100 µl) were preincubated with the peptides for 1 h before transfer to the upper  
chamber. The lower chamber contained 500 µl of the medium without the peptides.  
The cells were allowed to migrate to the lower surface of the membrane for 16 h and  
5 then stained with crystal violet and counted.

## RESULTS

### Identification of the $\alpha_M$ I domain-binding peptide motif D/E-/D/E-G/L-W

10 Using phage peptide display libraries, we selected peptides that interact with the  $\alpha_M$  I  
domain. GST-binding phage were first eliminated on GST-coated wells and the  
unbound phage preparations were incubated on  $\alpha_M$  I domain GST fusion protein-  
coated wells. The  $\alpha_M$  I domain-binding phage were enriched by three rounds of  
panning and the peptide sequences were determined. With the exception of one linear  
15 peptide, the peptides were derived from the cyclic CX<sub>7</sub>C and CX<sub>8</sub>C libraries. The I  
domain-binding sequences showed only one conserved motif, a somewhat unexpected  
finding in terms of the known ligand binding promiscuity of the I domain. The bound  
peptides contained two consecutive negatively charged amino acids, i.e. glutamatic  
and/or aspartic acids, followed by glycine and tryptophan residues (Fig. 1A). The  
20 consensus D/E-/D/E-G/L-W determined by this approach was clearly different from  
LLG-C4 and other  $\beta_2$  integrin-binding peptides reported so far.

We first prepared the phage display peptides as intein fusion proteins, from which the  
peptides were cleaved. This allowed us to rapidly test the peptide solubility and the  
25 binding specificity before large-scale chemical peptide synthesis. The peptides were  
cloned using oligonucleotide primers that amplify the peptide library insert from the  
phage vector. Consequently, all the peptides prepared contain the vector-derived  
sequences ADGA and GAAG in the NH<sub>2</sub>- and COOH- termini, respectively. Phage  
binding experiments using soluble peptides as competitors indicated that the peptides  
30 bearing the two adjacent negative charges bound to a common site (not shown). We  
chose the peptide ADGA-CILWMDDGWC-GAAG (DDGW) for further experiments  
as this peptide showed strong binding and was highly soluble in aqueous buffers  
(soluble in 50 mM NaOH at >10 mM concentrations). The peptide was also prepared

by chemical synthesis. The phage bearing the DDGW sequence avidly bound to the  $\alpha_M$  I domain and this was readily inhibited by low concentrations of the DDGW peptide, but only marginally affected by the LLG-C4 peptide, indicating different binding sites for DDGW and LLG-C4 (Fig. 1B). Control phage bearing other peptide sequences did not bind. The DDGW-bearing phage also showed also specific binding to the  $\alpha_L$  I domain that was inhibitable by DDGW but the interaction was weaker than with the  $\alpha_M$  I domain (Fig. 1C and data not shown). No binding was observed with the  $\alpha_X$  I domain or GST used as a control (Fig. 1C).

10 **Characterization of DELW sequence on the catalytic domain of gelatinases that mediates interaction with the  $\beta_2$  integrin I domains**

We searched protein databases for matches to the novel D/E-/D/E-G/L-W motif. One of the phage library-derived peptides, CPEELWWLC, was highly similar to the DELW(S/T)LG sequence present on the catalytic domain of MMP-2 and MMP-9 gelatinases (Fig. 1A). DELW-like sequences with double negative charges are also present in other secreted MMPs but not in the membrane-type MMPs such as MMP-14.

No MMP has been reported to bind to the leukocyte  $\beta_2$  integrins. We therefore set out 20 to study whether MMP-9 in particular could be a ligand of the  $\beta_2$  integrins as MMP-9 gelatinase is the major leukocyte MMP and is induced during  $\beta_2$  integrin activation. As a first step, we synthesized the whole proMMP-9 sequence as overlapping 20-mer peptides on a pepspot membrane. Binding assays with the  $\alpha_M$  I domain revealed a single active peptide that located to the MMP-9 catalytic domain (Fig. 1D). No 25 binding was observed, when the I domain was omitted and the membrane was probed with antibodies only. The sequence of the I domain-binding peptide was QGDAHFDDDELWSLGKGVVV and it contained the binding motif identified by phage display (Fig. 1D).

30 The active MMP-9 peptide contained four consecutive amino acids with negative charges, DDDE. To study the importance of these residues, the aspartic and glutamic acid residues that were closest to the tryptophan were replaced by alanines. At the same time the peptide length was shortened to 15-mer. The alanine mutagenesis

significantly abrogated I domain binding on the pepspot filter; the OD value dropped from 2010 to 476 (Table I). To study whether the negatively charged peptide from other MMPs is also active, we synthesized the corresponding 15-mers and the double alanine mutations. Sequences from MMP-1, 2, 3, 7, 8, 9 and 13, but not the membrane-anchored MMP-14 (MT1-MMP), could bind the  $\alpha_M$  I domain. Alanine mutations always decreased the binding.

We did similar pepspot analysis for some of the known I domain ligands, which contain D/E-/D/E-G/L-W like sequences. Peptides derived from myeloperoxidase, catalase, thrombospondin-1 and complement protein iC3b strongly bound the I domain in this assay and the double alanine mutation caused a loss of binding (see Table I). Of the three iC3b peptide permutations tested, ARSNLDEDIIAEENI was the active one. The acidic residues were followed by a hydrophobic isoleucine cluster in this peptide. The soluble DDGW peptide efficiently inhibited the binding of this peptide to the I domain. Weaker I domain binding was observed with one complement factor H-derived peptide and one fibronectin-derived peptide. Peptides derived from ICAMs-1, 2 and 3, neutrophil inhibitory factor, Cyr61, fibrinogen, GP1b, factor X, or E-selectin lacked activity.

Alanine scanning mutagenesis of the DDGW peptide with the pepspot system similarly indicated the importance of the glutamic acid residues for I domain binding (Fig. 1E). Alanine mutations of the glycine or either one of the tryptophan residues also inactivated the peptide. Mutations of the isoleucine, leucine or methionine residues were tolerated. Deletion of the ADGA sequence from the N terminus had no effect on I domain binding, but removal of the C terminal GAAG sequence abolished the binding. As the peptides were immobilized via the C terminus on the filter, a sufficient linker sequence such as GAAG seemed important. We also tested a series of truncated cyclic peptides to identify the shortest active sequence. This analysis showed that ADGA-CEDGWC-GAAG, but not ADGA-CDDGWC-GAAG was the minimal peptide that supported  $\alpha_M$  I domain binding. The longer side chain of glutamate compared to aspartate is probably required to bring the negatively charged carboxyl group in the correct position for I domain binding.

**Progelatinases bind to purified  $\alpha_M\beta_2$  and  $\alpha_L\beta_2$  integrins and their I domains**

We next used a microtiter well-based sandwich assay to study gelatinase binding to purified integrins. Progelatinases bound in a concentration-dependent manner to coated  $\alpha_M\beta_2$  integrin (Fig. 2A). Curiously, MMP-2 and MMP-9 lost the integrin

5 binding ability after activation by trypsin or APMA. The binding of proMMP-2 and proMMP-9 was observed with both  $\alpha_M\beta_2$  and  $\alpha_L\beta_2$  integrins and their corresponding I domains (Fig. 2B and 2C). No binding was detected on the  $\alpha_X$  I domain or the  $\alpha_1\beta_1$  and  $\alpha_3\beta_1$  integrins.

10 The DDGW peptide was an efficient inhibitor and it inhibited proMMP-9 binding to the  $\alpha_M$  I domain with an  $IC_{50}$  of 20  $\mu M$  (Fig. 3A and 3B). To demonstrate that the negative charges of aspartic acids are essential for the peptide activity, the peptide ADGACILWMKKKGWCGAAG (KKGW) containing lysines in place of aspartic acids was prepared. As expected, the KKGW peptide was inactive and did not  
15 compete with proMMP-9 binding. We were also interested in testing lovastatin, as its binding site in the  $\alpha_L$  I domain is known (34,35). Lovastatin was not able to compete with proMMP-9 even at a high concentration.

20 ProMMP-9 bound like a true integrin ligand, as the cation chelator EDTA (5 mM) nearly completely prevented the binding (Fig. 3C and 3D). For background measurement in the sandwich assay, we used antibodies alone (control), or coating with ICAM-1 or wild type GST. The gelatinase-binding peptide CTT (200  $\mu M$ ) inhibited proMMP-9-integrin interaction with the same efficiency as EDTA did. The control peptides STTHWGFTLS (STT) and CTTHAGFTLC (W $\rightarrow$ A CTT), which  
25 lack gelatinase inhibitory activity (26), were without effect. A non-peptide chemical MMP inhibitor (Inh1) also prevented proMMP-9 binding. As EDTA inhibits both the gelatinase and the integrin, we used integrin blocking antibodies and ligand peptides to demonstrate the specific binding activity of  $\beta_2$  integrin. The known ligand-binding blocking antibodies MEM 170, MEM 83, and LM2/1 inhibited proMMP-9 binding. A  
30 control antibody TL3 had no effect. The I domain binding peptide LLG-C4 showed a partial inhibitory effect. RGD-4C, a ligand of  $\alpha_V$  integrins, served as control peptide and had no effect on proMMP-9 binding. The purity of the integrins was typically

more than 90% and that of I-domains 95%, making it unlikely that progelatinases would bind to impurities in the preparations.

Progelatinase-integrin complexes were also obtained by co-precipitation experiments  
5 using HT1080 conditioned medium as a source of proMMP-9 and proMMP-2, which were analyzed by zymography. The progelatinases co-precipitated with  $\alpha_M\beta_2$  integrin or  $\alpha_M$  I domain GST fusion protein when these were used as a bait. The integrin added to the medium was immunoprecipitated with the  $\alpha_M$  antibody OKM10 (Fig. 4A). The  $\alpha_M$  I domain GST protein was pulled down with glutathione-beads (Fig. 10 4B). CTT but not STT had an inhibitory effect. Inhibition of the I domain by LM2/1, ICAM-1 or LLG-C4 also affected the pull-down of progelatinases. GST control did not coprecipitate the gelatinases. No active forms of gelatinases were found to coprecipitate with  $\alpha_M\beta_2$  or the I domain, when APMA-treated HT-1080 medium or APMA-activated MMP-9 was used (not shown).

15

As the gelatinase inhibitors CTT and Inh1 prevented the binding of proMMP-9 to the integrin, it can be anticipated that CTT and Inh1 avidly bind to proMMP-9. To gain more insight into this, we examined binding of proMMP-9 to immobilized CTT peptide. ProMMP-9 specifically bound to the CTT-GST fusion protein (Fig. 5A) but 20 not to LLG-C4-GST. CTT and Inh1 at 100  $\mu$ M concentrations effectively competed in binding but W $\rightarrow$ A CTT did not. The proMMP-9 preparation did not contain detectable amounts of active MMP-9 on zymography analysis, and after proMMP-9 activation with APMA, the CTT-GST binding increased. CTT and Inh1 could also bind to proMMP-9 secreted into the medium of PDBu-activated THP-1 leukemic cells 25 (Fig. 5B) or HT1080 fibrosarcoma cells (not shown). A time-dependent reduction in the gelatinolytic activity of proMMP-9 was observed with CTT (panel 1) and Inh1 (panel 3), but not with the W $\rightarrow$ A CTT peptide (panel 4). Western blot analysis indicated that CTT does not decrease the secretion of proMMP-9 by the cells (panel 2). Furthermore, the CTT complex was reversible and disappeared after repeated 30 freezing and thawing of the samples.

**Demonstration of a cell-surface complex between progelatinases and  $\beta_2$  integrins**

To study whether the progelatinases occur in a complex with the  $\beta_2$  integrins on the leukocyte surface, we performed immunoprecipitation and co-localization studies.

First, we examined THP-1 monocytic leukemia cells in the resting state and after

5 induction by PDBu, which mimics leukocyte activation *in vivo*. THP-1 cell-stimulation with PDBu led to upregulation of MMP-9 (data not shown). The cell

surface glycoproteins of THP-1 cells were labelled with tritium [<sup>3</sup>H] followed by immunoprecipitation with  $\beta_2$  integrin and MMP-9 antibodies. In the PDBu-activated

10 cells, the  $\alpha_M$  chain antibody OKM10 and  $\beta_2$  chain antibody 7E4 immunoprecipitated two [<sup>3</sup>H]-labelled proteins corresponding to the integrin  $\alpha_M$  chain (165 kDa) and  $\beta_2$

chain (95 kDa) (Fig. 6A, lanes 9-10). Importantly, polyclonal MMP-9 antibodies

immunoprecipitated the same two integrin chains (lane 7). In non-activated cells,

essentially no co-precipitation of  $\alpha_M$  and  $\beta_2$  were observed with MMP-9 antibodies,

although the  $\alpha_M$  and  $\beta_2$  chains were present. The co-precipitation of the integrin

15 chains by MMP-9 antibodies was prevented by the CTT peptide (lane 8). The control

antibody (TL3) did not precipitate any proteins.

With the [<sup>3</sup>H]-labelled cells, we did not observe any band corresponding to proMMP-9, perhaps because the carbohydrates of proMMP-9 are poorly labelled. We therefore

20 analyzed the PDBu-activated THP-1 cells by Western blotting (Fig. 6B). ProMMP-9 was readily immunoprecipitated with antibodies against MMP-9,  $\alpha_M$  or  $\alpha_L$ , but not by the control antibody. MMP-9 antibodies in turn were able to immunoprecipitate the

$\alpha_M$  but not the  $\alpha_L$  chain. MMP-2 antibodies similarly co-precipitated  $\alpha_M$  but not  $\alpha_L$ . When the cell lysate was precleared with the  $\alpha_M$  antibody OKM-10, the amount of

25 immunoprecipitated  $\alpha_M$  and proMMP-9 clearly decreased (lane 6). Preclearing with the  $\alpha_L$  antibody TS2/4 did not significantly remove  $\alpha_M$  or proMMP-9, but abolished the  $\alpha_L$  precipitation (lane 7).

As THP-1 cells do not express high amounts of the  $\alpha_L$  chain (20), we examined the

30 Jurkat T cell line, which expresses more  $\alpha_L$  than  $\alpha_M$  (28). We observed a significant immunoprecipitation of  $\alpha_L$  by MMP-9 and MMP-2 antibodies after PDBu activation

(Fig. 6C). Furthermore, the  $\alpha_L$  antibody co-precipitated more proMMP-9 in

comparison to the  $\alpha_M$  antibody. No proMMP-9 co-precipitated with MMP-2 antibodies in Jurkat or THP-1 cells.

ProMMP-9 and  $\alpha_M\beta_2$  were found to co-localize on the cell surface following PDBu-  
5 activation of THP-1 cells as studied by fluorescence and confocal microscopy (Figs.  
7A and 7B, respectively). Using a higher magnification, colocalization was primarily  
seen in cell surface clusters (Fig. 7B), and to a lesser extend on areas where cells  
contacted each other (not shown). We believe that the MMP-9 co-localizing with  
 $\alpha_M\beta_2$  is the proMMP-9, as the activated MMP-9 did not bind to  $\alpha_M\beta_2$ . Without PDBu-  
10 activation, there was hardly any co-localization of proMMP-9 and  $\alpha_M\beta_2$ . The  
secondary antibodies did not stain the cells when the primary antibodies were omitted  
(data not shown). When the cells were preincubated with the CTT peptide or  
recombinant soluble ICAM-1 to block proMMP-9 or  $\alpha_M\beta_2$ , the cell surface clusters  
did not form and the proMMP-9- $\alpha_M\beta_2$  colocalization was not observed (not shown).  
15 ProMMP-9- $\alpha_M\beta_2$  colocalization was also observed on Jurkat cells following phorbol  
ester stimulation (not shown).

**Blocking the progelatinase/ $\beta_2$  integrin complex with DDGW releases cell-bound  
proMMP-9 and inhibits cell migration but not adhesion**

As the DDGW peptide is an integrin ligand, one of the questions was whether it can  
support adhesion of leukocytes. We studied adhesion of human myelomonocytic  
THP-1 cells on immobilized glutaraldehyde-polymerized peptide. Phorbol-ester  
activated cells efficiently bound to the DDGW peptide, whereas there was no binding  
in the absence of cell activation (Fig. 8A). As a positive control, the recombinant  
20 intein-produced ADGA-CPCFLLGCC-GAAG peptide supported adhesion, but unlike  
the DDGW peptide, it also supported adhesion in the absence of integrin activation.  
The acute myeloid leukemic cell line OCI/AML-3 also avidly adhered to DDGW,  
whereas human fibrosarcoma HT1080 cells which lack  $\beta_2$  integrins did not (not  
shown). As THP-1 cells were able to adhere on DDGW, we next studied the effect of  
25 the peptide on  $\beta_2$  integrin dependent adhesion to fibrinogen and ICAM-1.  
Interestingly, DDGW did not block cell adhesion to fibrinogen, whereas the LLG-C4  
peptide blocked the adhesion as previously reported (Fig. 8B). Similarly, DDGW did  
not block the binding of recombinant  $\alpha_M$  I-domain to immobilized fibrinogen (not  
30 shown).

shown). DDGW did not either block cell adhesion on ICAM-1-Fc fusion protein. As a control, the blocking antibody 7E4 against  $\beta_2$  integrins prevented the ICAM-1 binding, indicating that the THP-1 cells bound in a  $\beta_2$  integrin dependent manner (Fig. 8C). We also found no blocking effect of DDGW on THP-1 adhesion to LLG-C4-GST fusion protein (not shown).

The second question raised by these studies was whether the DDGW peptide can release cell-bound proMMP-9. When THP-1 cells were cultured for 48 h in the presence of DDGW, an increase of proMMP-9 level was observed in the conditioned medium as studied by gelatin zymography (Fig. 8D). The peptide increased both monomeric and dimeric proMMP-9 in the culture medium. In contrast, CTT slightly decreased or inhibited active proMMP-9. KKGW and W→A CTT had no effect.

Finally, we studied the role of the progelatinase/ $\beta_2$  integrin complex in leukocyte migration using a transwell assay in which leukocyte migration can be adjusted by the choice of coated matrix or ligand protein. We tested that the CTT, LLG and DDGW peptides are not toxic to the THP-1 cells in a 48 h time frame at >200  $\mu\text{M}$  concentrations using an MTT assay. Using transwells coated with 10% serum in cell culture medium, we first studied the effect of peptides on the basal migration of THP-1 cells in the absence of any stimulus by phorbol ester or an adhesive matrix. Under such conditions, CTT, LLG-C4 or the gelatinase inhibitor Inhl at a 200  $\mu\text{M}$  concentration had no effect on THP-1 migration indicating no active involvement of gelatinases or  $\beta_2$  integrins (Fig. 9A). We have previously shown that when the transwells are coated with LLG-C4-GST fusion protein, THP-1 cells adhere and migrate in a  $\beta_2$  integrin dependent manner (14). Thus, transwells were coated with LLG-C4-GST fusion protein or GST alone. Both the DDGW and CTT peptide, but not KKGW, inhibited the migration of THP-1 cells on the LLG-C4-GST substratum (Fig. 9B). The soluble LLG-C4 peptide also blocked the migration. In the presence of GST coating, cell migration was negligible. To verify that the effect of DDGW peptide was  $\beta_2$  integrin dependent, HT1080 fibrosarcoma cells lacking these integrins were allowed to migrate in the presence of CTT, DDGW, KKGW or LLG-C4. Of these peptides, only CTT was capable of inhibiting cell migration (Fig. 9C).

## DISCUSSION

5 Analysis of  $\alpha_M$  I domain-binding peptides led to the finding that MMPs, particularly the MMP-9 and MMP-2 progelatinases, are potent  $\beta_2$  integrin ligands. Our studies show that proMMP-9, the major MMP of activated leukocytes, is co-localized with the  $\beta_2$  integrin on the cell surface. Cell surface labelling and co-immunoprecipitation further demonstrates the occurrence of the complex in leukemic cell lines. Finally, we  
10 have found evidence that this proteinase-integrin complex plays a role in migration of the leukemic cells.

Although phage display has been extensively used with whole integrins (14,36-44), to the best of our knowledge, this is the first successful phage display selection on an  
15 isolated integrin I domain. We could enrich only one binding motif even though the  $\alpha_M$  I domain can bind a variety of ligands (1-3). The peptide motif we isolated could not compete with the ICAM-1, fibrinogen, or LLG-C4 ligands. The success of phage display depends on the libraries used and the biopanning conditions. Our method favoured "high affinity" interactions with the cyclic peptides yielding the D/E-D/E-G/L-W motif. Interestingly, this motif shows a high degree of similarity to the CWDD(G/L)WLC peptide isolated by phage display as an RGD sequence-binding peptide (40). By recognizing the RGD ligand sequence, CWDDGWLC structurally and functionally behaves like a minimal integrin. Here, we have identified the DDGW peptide in a reverse situation, as a ligand to integrin. However, the RGD sequence  
20 does not compete with the  $\alpha_M$  I domain as the GRGDSP peptide at a 1 mM concentration was unable to inhibit proMMP-9 binding to the I domain<sup>2</sup>. It will be interesting to see whether the DDGW peptide recognizes a positively and negatively charged sequence in the I domain.  
25

30 Some hints for the binding site of DDGW come from the interaction of iC3b with  $\alpha_M\beta_2$  integrin. Our pepspot analysis showed that the iC3b peptide ARSNLDEDIIAEENI, but not the control peptide ARSNLDAAIIAEENI, bound the  $\alpha_M$  I domain and the DDGW peptide blocked this binding. The DEDIIAEENI

sequence with multiple adjacent negative charges is required for efficient binding of iC3b to  $\alpha_M\beta_2$  integrin (45). The binding site of complement protein iC3b in the I domain has been mapped indicating a role for the positively charged amino acid residue K<sup>245</sup> for iC3b binding (46). Mutation of this residue does not affect the  
5 binding of the fibrinogen recognition peptide (47). This may account for the inability of the DDGW peptide to inhibit ICAM-1 and fibrinogen-mediated cell adhesion. These findings suggest that the K<sup>245</sup> residue is the positively charged contact site for the DDGW peptide and the D/E-D/E-G/L-W motif as well.

10 The pepspot analysis indicates that a class of  $\beta_2$  integrin ligands contains an active D/E-D/E-G/L-W motif. These include the previously identified  $\alpha_M\beta_2$  ligands iC3b, thrombospondin-1, and the enzymes myeloperoxidase and catalase (3,4,5,48). In our experiments, the peptides derived from several secreted MMPs, but not membrane-bound MT1-MMP, were also active. It is notable that the D/E-D/E-G/L-W motif is  
15 relatively conserved in the secreted members of the MMP family. Whether other MMPs in addition to the progelatinases can make  $\beta_2$  integrin complexes, remains to be determined.

20 Finding of a dominant integrin-binding site in the catalytic domain of proMMP-9 was unexpected, because previous studies suggested an essential role for another MMP domain, the hemopexin domain, in integrin binding. The hemopexin domains mediated MMP-2 binding to the  $\alpha_V\beta_3$  integrin (49-51) and MMP-1 binding to the  $\alpha_2\beta_1$  integrin (52,53). The cleaved hemopexin domain of MMP-2 has also been shown to occur in vivo and to inhibit angiogenesis (50). Understandably, phage peptide  
25 display and pepspot techniques have limitations and only linear peptide sequences can be analysed, not protein conformations. Thus, in the present study we cannot make conclusions of the function of separate MMP-9 domains in integrin binding and it remains to be seen whether cleavage products of MMP-9, if present in vivo, can act as  $\beta_2$  integrin ligands. Our studies suggest that the peptide sequence from the catalytic  
30 domain is essential for the binding of full-length proMMP-9 to the  $\beta_2$  integrin, as the synthetic DDGW peptide could completely inhibit the integrin binding. It was important to use natural proMMP-9 because  $\alpha_M\beta_2$  is known to bind to denatured proteins and this may sometimes be the case for bacterially expressed proteins (4).

Furthermore, we did not observe binding of an active MMP-2 or MMP-9 to the integrin, although the DELW(T/S)LG sequence should remain unchanged in the active enzyme. We rather found that AMPA and trypsin, activators of proMMP-9, released MMP-9 from THP-1 cells, apparently affecting the integrin complex<sup>3</sup>. These 5 results suggest that the proenzyme presents the integrin binding site more efficiently than the active enzyme and the  $\beta_2$  integrin may even control the activation of the proenzyme.

In the three-dimensional structures of proMMP-2 and -9 (54,55), the I domain 10 binding site is located in the vicinity of the zinc-binding catalytic sequence HEFGHALGLDH between the catalytic domain and the fibronectin type II repeats. This location suggests a mechanism for evading proMMP-9 inhibition by tissue inhibitors of MMPs (TIMPs) or  $\alpha_2$ -macroglobulin. In the absence of inhibitors, the 15 cell surface-localized proMMP-9 would be readily susceptible for activation and substrate hydrolysis, which may also occur in the presence of intact propeptide (56). On the other hand, because the binding site of the I domain is located in the vicinity of the catalytic groove, it also suggests an explanation for the blocking of MMP-9/ $\beta_2$  integrin interaction by the small molecule MMP inhibitors such as CTT and Inh1.

The activity of the DDGW peptide in the THP-1 cell migration assay suggests an 20 important function for the integrin-progelatinase complex in leukocyte migration. Obviously, we cannot exclude the possibility that the DDGW peptide blocks binding of other ligands than gelatinases and in this way inhibits the leukocyte migration. However, as the specific gelatinase inhibitor CTT also blocks the THP-1 cell 25 migration, these results strongly suggest that the proMMP-9/ $\beta_2$  integrin complex is the main target for DDGW. Interestingly, the DDGW peptide blocked THP-1 cell migration although it increased the level of proMMP-9 in the medium, which suggests that cell-surface bound rather than total MMP-9 level is a critical factor in cell migration.

## FIGURE LEGENDS

5 FIG. 1. Identification of an I domain binding site in progelatinase. A, Phage display peptide sequences specifically bound to the  $\alpha_M$  I domain. The consensus motif is shown in bold. Peptides with the strongest binding (CILWMDDGW) and the highest similarity (CPEELWWLC) are aligned with human MMPs (accession numbers shown in parenthesis). B, Phages bearing the CILWMDDGWC peptide or a  
 10 control peptide were allowed to bind to immobilized  $\alpha_M$  I domain-GST fusion protein (20 ng/well) in the absence or presence of 15  $\mu$ M DDGW peptide or LLG-C4 peptide. Bound phages were detected using a monoclonal anti-M13 phage antibody. Mean absorbance of triplicate samples  $\pm$  SD is shown. C,  $\alpha_L$ ,  $\alpha_M$ , or  $\alpha_X$  I domain-GST fusions were coated on microtiter wells as in B, and the binding of CILWMDDGWC  
 15 peptide bearing phage or a control phage was measured. D, Peptides covering the complete sequence of proMMP-9 were synthesized as overlapping peptides on a pepspot membrane. The  $\alpha_M$  I domain (0.5  $\mu$ g/ml) was allowed to bind to the peptides followed by immunodetection using anti- $\alpha_M$  I domain antibody LM2/1. The  $\alpha_M$  I domain-binding peptide 13 (arrow) is shown in boldface and the zinc binding catalytic  
 20 sequence is underlined. The prodomain (Pro), catalytic domain containing the fibronectin type II repeats (Cat) and hemopexin domain (Pex) are marked to illustrate the domain structure of proMMP-9. E, Alanine-mutated and truncated peptides were synthesized on a pepspot filter and probed with the recombinant  $\alpha_M$  I domain (5  $\mu$ g/ml). Bound I domain was measured using mAb MEM-170 (5  $\mu$ g/ml) followed by  
 25 HRP-conjugated anti-mouse secondary antibody and ECL detection. The binding was quantified by densitometric scanning. The bars show  $\alpha_M$  I domain binding to single peptide spots as arbitrary optical density units/mm<sup>2</sup>. Similar results were obtained in three independent experiments.

30 FIG. 2. Binding of progelatinases to purified integrins and I-domains. A, proMMP-9, proMMP-2 or their trypsin-activated forms, at the concentrations indicated, were allowed to bind to  $\alpha_M\beta_2$  integrin-coated wells. Appropriate MMP antibodies were used to determine binding. The results in this and other figures are

represented as the means  $\pm$  SD from triplicate wells. B, binding of proMMP-9 (80 ng/well) was examined on microtiter wells coated with an integrin ( $\alpha_L\beta_2$ ,  $\alpha_M\beta_2$ ,  $\alpha_1\beta_1$ ,  $\alpha_3\beta_1$ ) or an I-domain ( $\alpha_L$ ,  $\alpha_M$ ,  $\alpha_X$ ). The binding was determined using anti-MMP-9 antibody. C, proMMP-2 (80 ng/well) was allowed to bind to  $\alpha_L\beta_2$ ,  $\alpha_M\beta_2$ ,  $\alpha_1\beta_1$  or the I-domains  $\alpha_L$ ,  $\alpha_M$  or  $\alpha_X$ . The binding was determined using an anti-MMP-2 antibody.

**FIG. 3. Inhibitors of the proMMP-9 /  $\beta_2$  integrin complex.**

A,  $\alpha_M$  and  $\alpha_L$  I domain-GST fusions were immobilized on microtiter wells. ProMMP-9 (100 ng/well) was added in the presence or absence of various peptides (200  $\mu$ M) or lovastatin (100  $\mu$ M) in a buffer containing 0.5% BSA. ProMMP-9 binding was detected using a monoclonal antibody against MMP-9. The results are shown as percent binding compared to binding in the absence of inhibitors (100%) and no proMMP-9 added (0%). B, DDGW peptide blocks proMMP-9 binding to  $\alpha_M$  in a dose dependent manner. The assay was done similarly as in (A), except various concentrations of peptides were added to compete for binding. All samples were assayed as triplicates and results shown are means  $\pm$  SD from a representative experiment. C, proMMP-9 binding to  $\alpha_M\beta_2$  and  $\alpha_L\beta_2$  was examined in the absence and presence of EDTA (5 mM), MMP inhibitor-1 (100  $\mu$ M), CTT (200  $\mu$ M), STT (200  $\mu$ M), MEM170 (40  $\mu$ g/ml), or control TL3 antibody (40  $\mu$ g/ml). The background of primary and secondary antibodies was measured by omitting proMMP-9 from the wells or by coating with ICAM-1. D, proMMP-9 binding to purified  $\alpha_M$  and  $\alpha_L$  I-domain GST fusion proteins or wild type GST was studied in the absence or presence of competitors as indicated. Control shows the background when proMMP-9 was omitted.

25

**FIG. 4. Coprecipitation of progelatinase with  $\beta_2$  integrin.** A,  $\alpha_M\beta_2$  integrin (3  $\mu$ g) was incubated with a 500  $\mu$ l sample of HT1080 medium containing proMMP-9 and proMMP-2 in the absence or presence of CTT or STT (200  $\mu$ M) for 2 h. The integrin was immunoprecipitated with the OKM10 antibody, and the immunoprecipitates were analyzed by gelatin zymography. In control experiments, integrin was omitted from the medium and ICAM-1 was added instead. B, a 500  $\mu$ l sample of HT1080 medium containing proMMP-9 and proMMP-2 was incubated with the  $\alpha_M$  I-domain GST (3 $\mu$ g) or LLG-C4-GST control. ICAM-1, LM2/1, CTT, STT, or LLG-C4 were used as

competitors. GST was pulled down with glutathione beads, and bound proteins were analyzed by zymography. The lane 1 in the figure insert: the proMMP-2 and proMMP-9 zymogens present in non-treated HT1080 medium, lane 2: lack of gelatinases pulled down with control LLG-C4-GST, lane 3: proMMP-9 and proMMP-  
5 2 coprecipitated by  $\alpha_M$  I domain GST fusion protein.

**FIG. 5. CTT peptide binds to both latent and active MMP-9.**

A, Binding of proMMP-9 or APMA-activated MMP-9 to CTT-GST was examined in the absence or presence of competitors CTT (100  $\mu$ M), W $\rightarrow$ A mutant CTT (100  $\mu$ M),  
10 and Inh1 (100  $\mu$ M). GST control was LLG-C4-GST. Binding was determined as in Figs. 2 and 3. The background in the absence of proMMP-9 is shown. D, THP-1 cells were incubated in serum-free medium containing CTT, Inh1 or W $\rightarrow$ A CTT at 200  $\mu$ M concentration. Samples from the media were collected at the time points indicated and analyzed by zymography (panels 1, 3, and 4) or Western blotting (panel 2).

15

**FIG. 6. Progelatinases occur in complex with  $\alpha_M\beta_2$  and  $\alpha_L\beta_2$  in PDBu-activated THP-1 and Jurkat cells.** A, THP-1 cell surface proteins were [ $^3$ H]-labelled using periodate-tritiated borohydride and analyzed by immunoprecipitation. CTT was used as a competitor (200  $\mu$ M). The immunoprecipitated samples were resolved on a 8-  
20 16% polyacrylamide gel, and the film was exposed for 3 days. Lanes 1-4 are from non-activated cells and lanes 6-10 from PDBu-activated cells. Lane 5 shows molecular weight markers. B, lysates from PDBu-activated THP-1 cells were immunoprecipitated with integrin or MMP antibodies followed by Western blotting with  $\alpha_M$  (OKM10),  $\alpha_L$  (TS2/4) or MMP-9 antibodies. Preclearings of the cell lysates  
25 were done using  $\alpha_M$  (lane 6) and  $\alpha_L$  (lane 7) antibodies. C, lysates from PDBu-activated Jurkat cells were subjected to immunoprecipitation followed by blotting with the  $\alpha_L$  (MEM83) and MMP-9 antibodies.

**FIG. 7. PDBu-induced colocalization of  $\alpha_M\beta_2$  and proMMP-9 in THP-1 cells.**

30 Cells were preincubated for 30 min at +37°C with 50 nM PDBu. A, cells were treated with anti- $\alpha_M$  OKM10 and anti-MMP-9 antibodies followed by FITC-labeled (green fluorescence) and TRITC-labeled (red fluorescence) secondary antibodies. Yellow color indicates colocalization of  $\alpha_M\beta_2$  and proMMP-9. Bars, 8.5  $\mu$ m. B,

immunofluorescence staining shows intense colocalization of MMP-9 (polyclonal antibody) and  $\alpha_M\beta_2$  integrin (OKM-10) on the surface of PDBu-activated THP-1 cells at higher magnification as visualized by confocal microscopy (Bars, 2.5  $\mu\text{m}$ ).

5 FIG. 8. The DDGW peptide supports THP-1 cell adhesion and induces proMMP-  
9 release, but does not block adhesion to the major  $\beta_2$  integrin ligands fibrinogen  
and ICAM-1. A, THP-1 cells were allowed to bind to immobilized, glutaraldehyde  
polymerized peptides with or without phorbol ester activation (50 nM) and the  
adherent cells were quantitated by phosphatase assay. THP-1 cells were allowed to  
10 bind to immobilized fibrinogen B, or recombinant ICAM-1-Fc C, in the presence or  
absence of 200  $\mu\text{M}$  soluble peptides. All samples were assayed as triplicates and  
results show means  $\pm$  SD. Identical results were obtained in two other independent  
experiments. D, THP-1 cells were incubated in the presence or absence of peptides at  
200  $\mu\text{M}$  concentration for 48 hours. Aliquots of conditioned medium were analyzed  
15 by gelatin zymography. Arrows show the 92 kDa proMMP-9 and 220 kDa proMMP-9  
dimer.

FIG. 9. Peptide inhibition of THP-1 cell migration. THP-1 cells were preincubated  
with the peptide as indicated at a 200  $\mu\text{M}$  concentration for 1 h at room temperature  
20 and applied to transwells in the absence A, or presence B, of LLG-C4-GST coating.  
Cells were allowed to migrate for 16 hours at +37°C. Cells migrated to the lower  
surface of the filter were stained and counted microscopically. C, HT1080  
fibrosarcoma cell migration was similarly assayed in the absence of LLG-C4-coating.  
The bars show means  $\pm$  SD from triplicate wells.

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#### Footnotes

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<sup>1</sup>The abbreviations used are: APMA, aminophenylmercuric acetate;  $\alpha_M\beta_2$ , CD11b/CD18, Mac-1 integrin; CTT, CTTHWGFTLC peptide; DDGW, ADGACILWMDDGWCGAAG peptide; GST, glutathione-S-transferase; ICAM, intercellular adhesion molecule; Inh1, matrix metalloproteinase inhibitor 1; KKGW, ADGACILWMKKGWCGAAG peptide; LLG-C4, CPCFLLGCC peptide; MMP, matrix metalloproteinase; RGD-C4, ACDCRGDCFCG peptide; STT, STTHWGFTLC peptide; W→A CTT, CTTHAGFTLC peptide.

<sup>2</sup>M.B. and E.K, unpublished observations.

<sup>3</sup>M.S. and E.K, unpublished observations.

15

**Table I: Pepspot analysis of peptides derived from MMPs and  $\alpha_M\beta_2$  integrin ligands**

Protein	Peptide	OD/mm <sup>2</sup>	Binding positivity
MMP-1	DAHFDEDERWTNNFR	1792 +	
	DAHFDEAARWTNNFR	1417 -	
MMP-2	DSHFDDDELWTLGEG	4687 +++	
	DSHFDDAAALWTLGEG	3334 ++	
MMP-3	DAHFDDDEQWTKDTT	4993 +++	
	DAHFDDAAQWTKDTT	2188 +	
MMP-7	DAHFDEDERWTDGSS	4043 ++	
	DAHFDEAARWTDGSS	2065 +	
MMP-8	DAHFDAEETWTNTSA	4295 ++	
	DAHFDAAAATWTNTSA	1258 -	
MMP-9	DAHFDDDELWSLGKG	2010 +	
	DAHFDDAAALWSLGKG	476 -	
MMP-13	DAHFDDDETWTSSSK	4324 ++	
	DAHFDDAAATWTSSSK	1732 +	
MMP-14	DTHFDSEAEPWTVRNE	1264 -	
	DTHFDSEAAPWTVRNE	1198 -	
MMP-1	SGDVQLDDIDGIQAI	484 -	
	SGDVQLAAIDGIQAI	441 -	
MMP-3	RFLRLSQDDINGIQSL	810 -	
	RFLRLSQAAINGIQSL	1541 +	
MMP-8	NYSLPQDDIDGIQAI	3348 ++	
	NYSLPQAAIDGIQAI	505 +	
MMP-13	HFMLPDDDVQGIQSL	542 -	
	HFMLPDAAVQGIQSL	384 -	
MMP-14	NFVLPPDDRRGIQQL	518 -	
	NFVLPAARRGIQQL	609 -	
Fibronectin	HEATCYDDGKTYHVG	1271 -	
	HEATCYAAGKTYHVG	596 -	
ICAM-3	LNATESDDGRSFFCS	369 -	
	LNATESAAGRSFFCS	277 -	
Complement factor H	EEMHCSDDGFWSKEK	2972 +	
TSP-1	EEMHCSAAGFWSKEK	321 -	
	WPSDSADDGWSPWSE	4655 +++	
NIF	WPSDSAAAGWSPWSE	1543 +	
	DPVCIPDDGVCFIGS	221 -	
ICAM-2	DPVCIPAAGVCFIGS	114 -	
	NSTADREDGHNFSC	75 -	
Fibronectin	NSTADRAAGHRNFSC	73 -	
	NVYQISEDGEQSLIL	1260 -	
Fibronectin	NVYQISAAGEQSLIL	453 -	
	VTYSSPEDGIHELP	301 -	
Cyr61	VTYSSPAAGIHELP	212 -	
	KMRFRCEDGETFSKN	317 -	

Myeloperoxidase	KMRFRCAAAGETFSKN WLPAEYEDGFSLPYG	386 - 4603 +++
Catalase	WLPAEYAAGFSLPYG AVKFYTEDGNWDLVG	924 - 5045 +++
Fibrinogen alpha	AVKFYTAAGNWDLVG KEVVTSEDGSDCPEA	690 - 124 -
Fibrinogen beta	KEVVTSAAAGSDCPEA RKQCSKEDGGWWYN	225 - 483 -
Fibrinogen alpha	RKQCSKAAGGGWWYN GFGSLNDEGEGEFWL	325 - 732 -
GP1b	GFGSLNAAGEGEFWL GCPTLGDEGDTDLYD	397 - 544 -
ICAM-1	GCPTLGAAGDTDLYD VSVTAEDEGTQRLTC	238 - 51 -
Factor X	VSVTAAAGTQRLTC DRNTEQEEGGEAVHE	68 - 379 -
E-selectin	DRNTEQAAGGEAVHE TCTFDCEEGFELMGA	236 - 309 -
E-selectin	TCTFDCAAGFELMGA SCNFTCEEGLQGP	70 - 138 -
E-selectin	SCNFTCAAGFMLQGP SCAFSCEEGLHGS	54 - 236 -
Fibronectin	SCAFSCAAGFELHGS TFHKRHEEGHMLNCT	74 - 39 -
Fibronectin	TFHKRHAAGHMLNCT VEYELSEEGDEPQYL	12 - 3676 ++
	VEYELSAAGDEPQYL	2682 +

Range: 0-1499 OD/mm<sup>2</sup> = -, 1500-2999 = +, 3000-4499 = ++,  
>4500 = +++

	Peptide	No competitor	Soluble DDGW
DDGW peptide	ADGACILWMDDGWC GAAG	10859	0
iC3b	ARSNLDEDIIAEENI ARSNLDAAIIAEENI	13265	409
iC3b	EDIIAEENIVSRSEF EDIIAAAANIVSRSEF	0	0
iC3b	EGVQKEDIPPADLSD EGVQKAAIPPADLSD	0	0

## CLAIMS

1. A compound inhibiting the leukocyte progelatinase/ $\beta_2$ -integrin complex, the compound comprising the tetrapeptide motif D/E-D/E-G/K-W.

5

2. The compound according to claim 1, wherein the tetrapeptide motif is DDGW.

3. The compound according to claim 1 or 2 for use as a pharmaceutical.

10 4. The compound according to claim 1 or 2 for use in inhibiting leukocyte migration.

5. A pharmaceutical composition comprising the compound according to claim 1 or 2, and a pharmaceutically acceptable carrier.

15 6. Use of the compound according to claim 1 or 2 for the manufacture of a pharmaceutical composition for the treatment of conditions dependent on leukocyte migration.

20 7. Use according to claim 6 for the manufacture of a pharmaceutical composition for inhibiting the adhesion of progelatinases to  $\beta_2$ -integrins.

8. The compound according to claim 1 or 2 for use in prevention of inflammatory conditions.

25 9. The compound according to claim 1 or 2 for use in prevention of leukaemia cell migration.

10. The compound according to claim 1 or 2 for use in treatment of leukaemia.

30

## SUMMARY

The  $\alpha_M\beta_2$  integrin of leukocytes can bind a variety of ligands. We screened phage display libraries to isolate peptides that bind to the  $\alpha_M$  I-domain, the principal ligand binding site of the integrin. Only one peptide motif, D/E-/D/E-G/L-W, was obtained with this approach in spite of the known ligand binding promiscuity of the I-domain. Interestingly, such negatively charged sequences are present in many known  $\beta_2$  integrin ligands and also in the catalytic domain of matrix metalloproteinases (MMPs). We show that purified  $\beta_2$  integrins bind to proMMP-2 and proMMP-9 gelatinases and that the negatively charged sequence of the MMP catalytic domain is an active  $\beta_2$  integrin-binding site. Furthermore, a synthetic DDGW-containing phage display peptide inhibited the  $\beta_2$  integrin's ability to bind progelatinases, but did not inhibit the binding of cell adhesion-mediating substrates such as intercellular adhesion molecule-1 (ICAM-1), fibrinogen, or an LLG-containing peptide. Immunoprecipitation and cell surface labelling demonstrated complexes of proMMP-9 with both the  $\alpha_M\beta_2$  and  $\alpha_L\beta_2$  integrins in leukocytes, and proMMP-9 colocalized with  $\alpha_M\beta_2$  in cell surface protrusions. The DDGW peptide and the gelatinase specific inhibitor peptide CTTHWGFTLC (CTT) blocked  $\beta_2$  integrin-dependent leukocyte migration in a transwell assay. These results suggest that leukocytes may move in a progelatinase- $\beta_2$  integrin complex dependent manner.

Figure 1

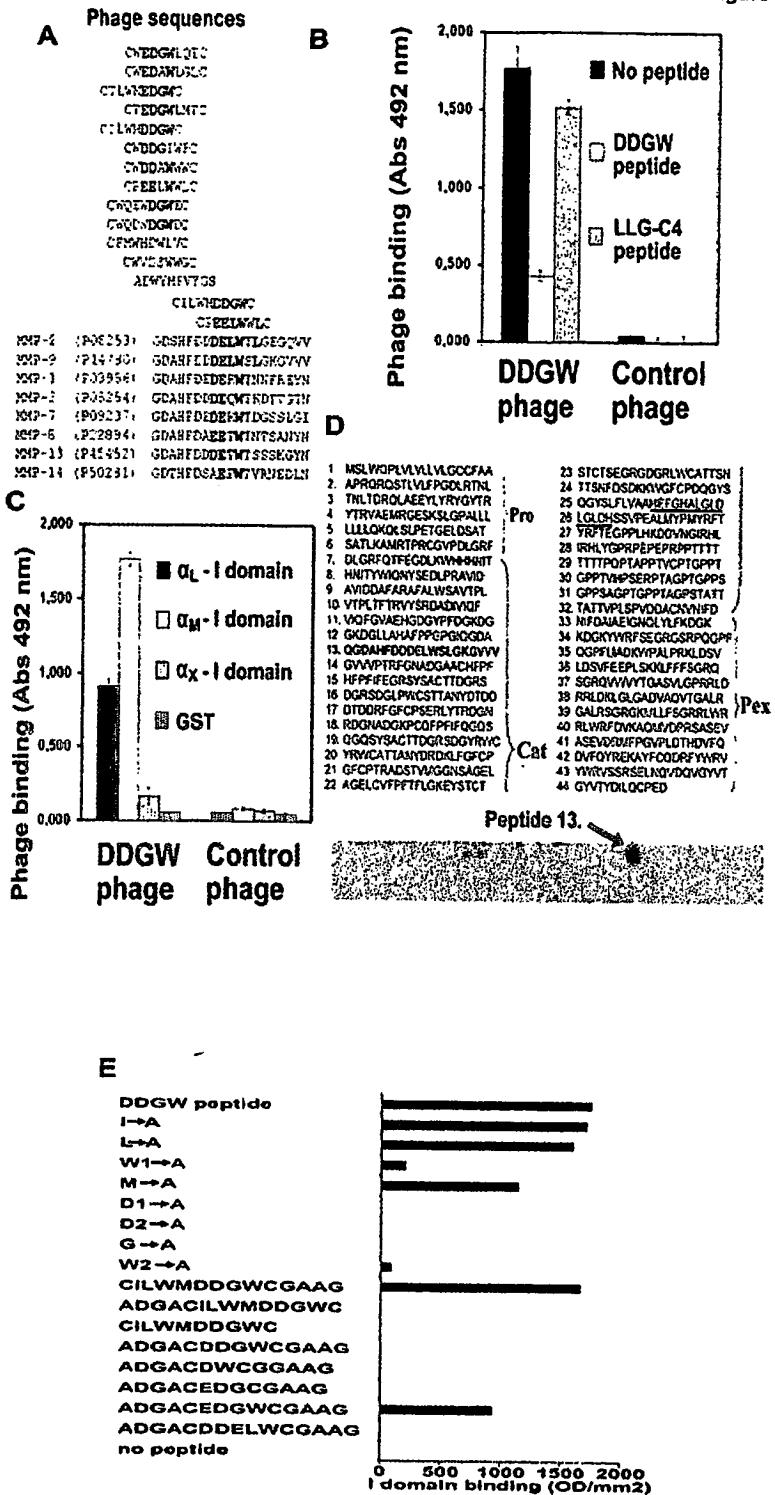


Figure 2

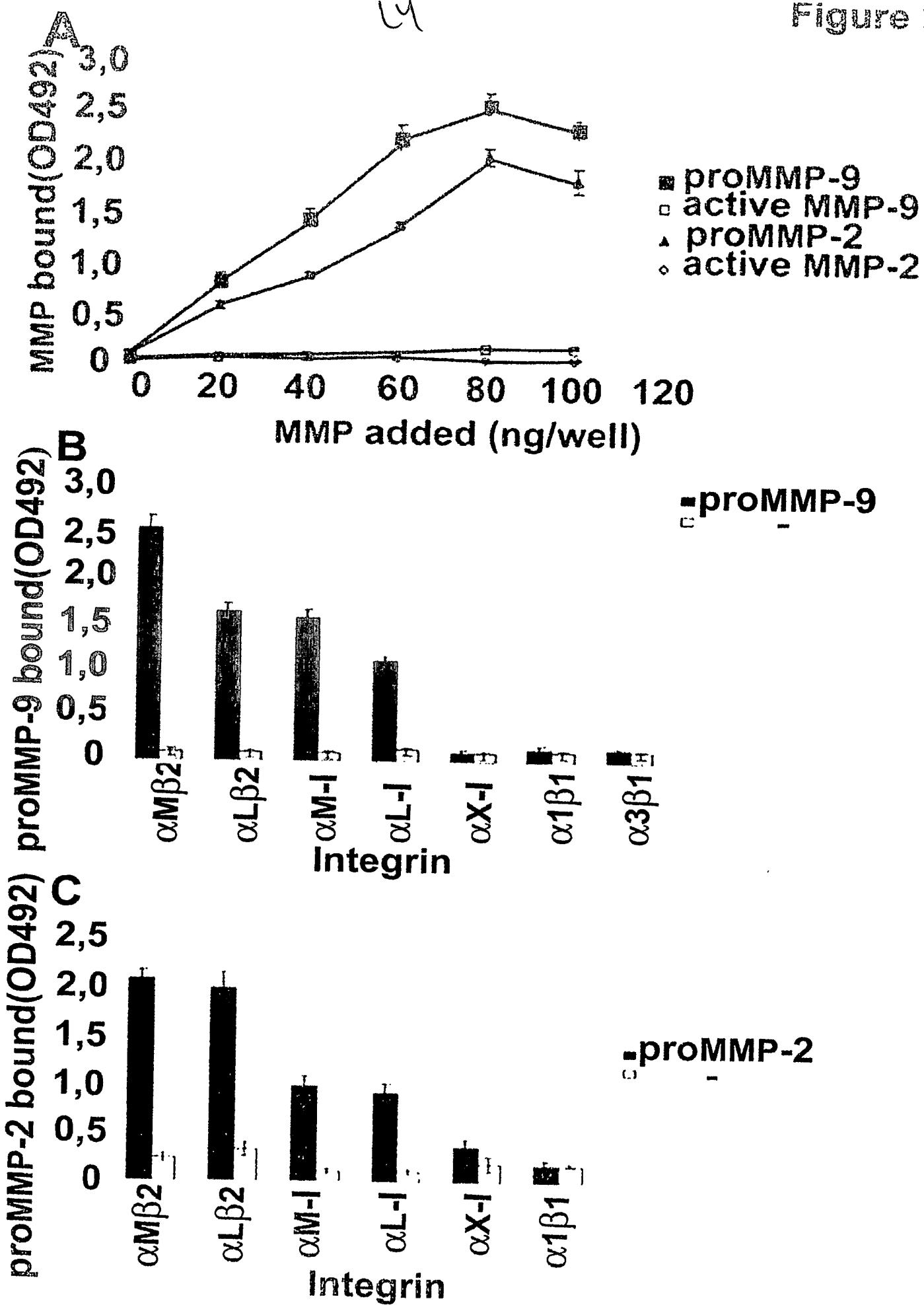


Figure 3

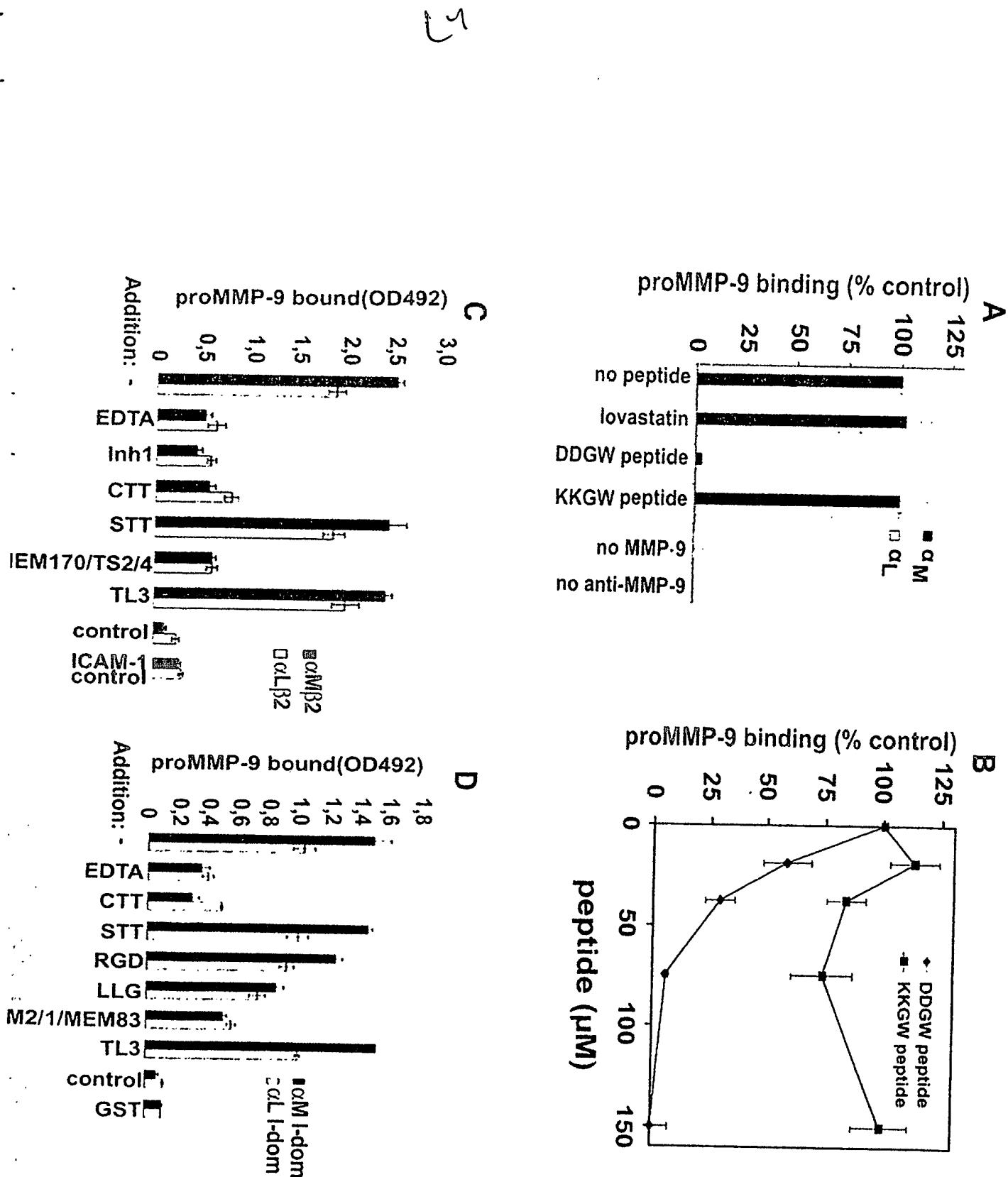
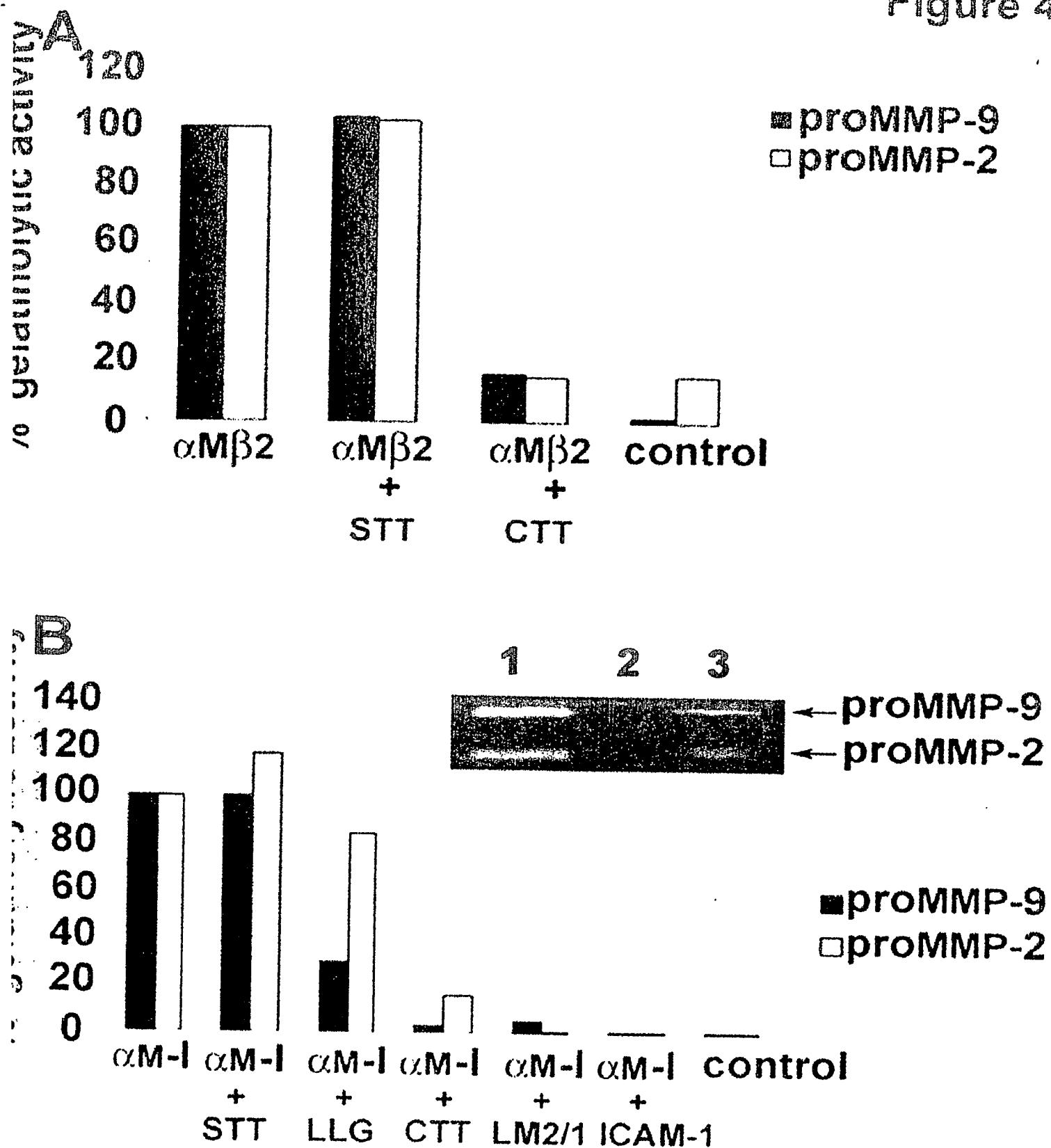


Figure 4



**Figure 5**

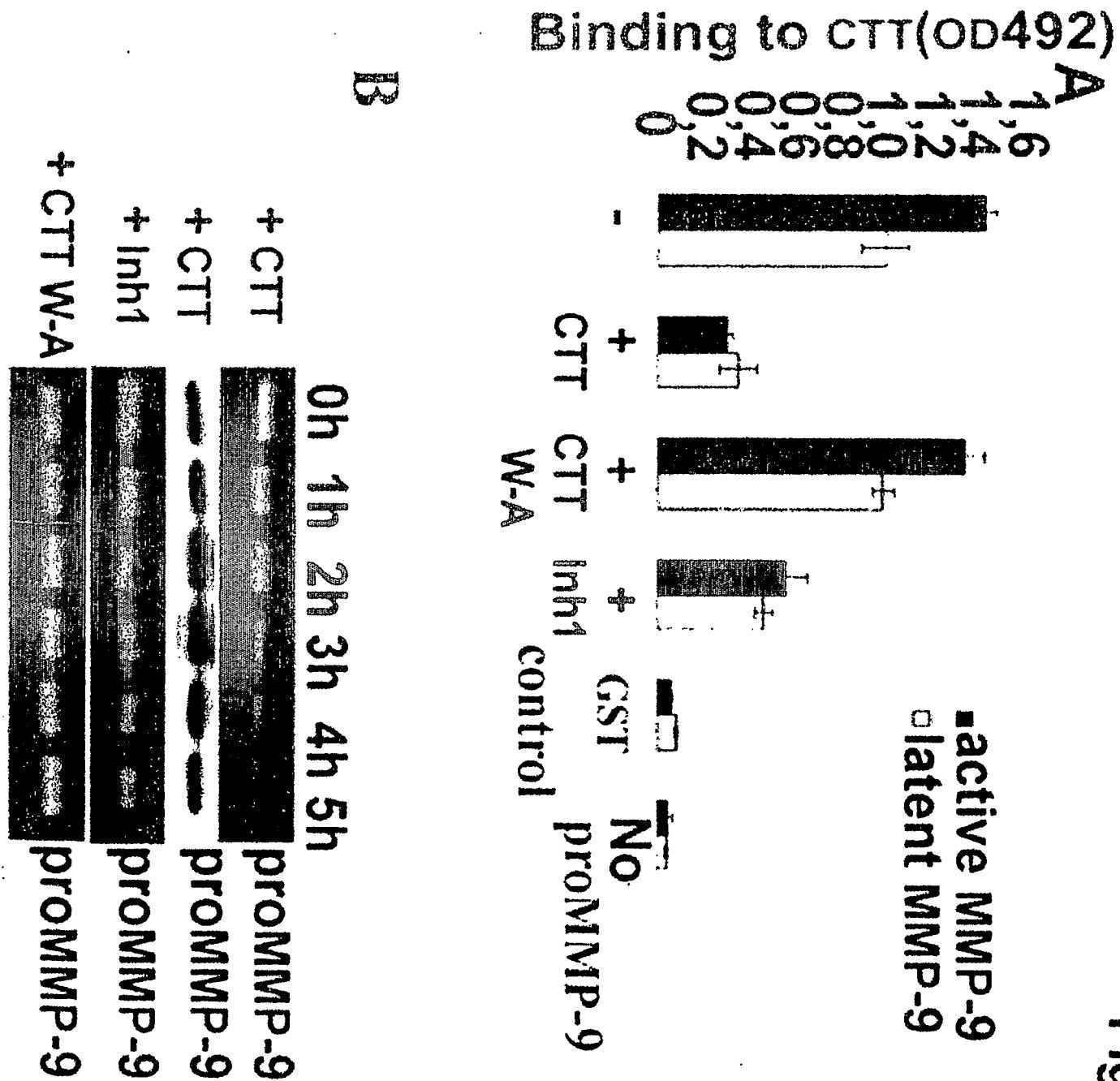
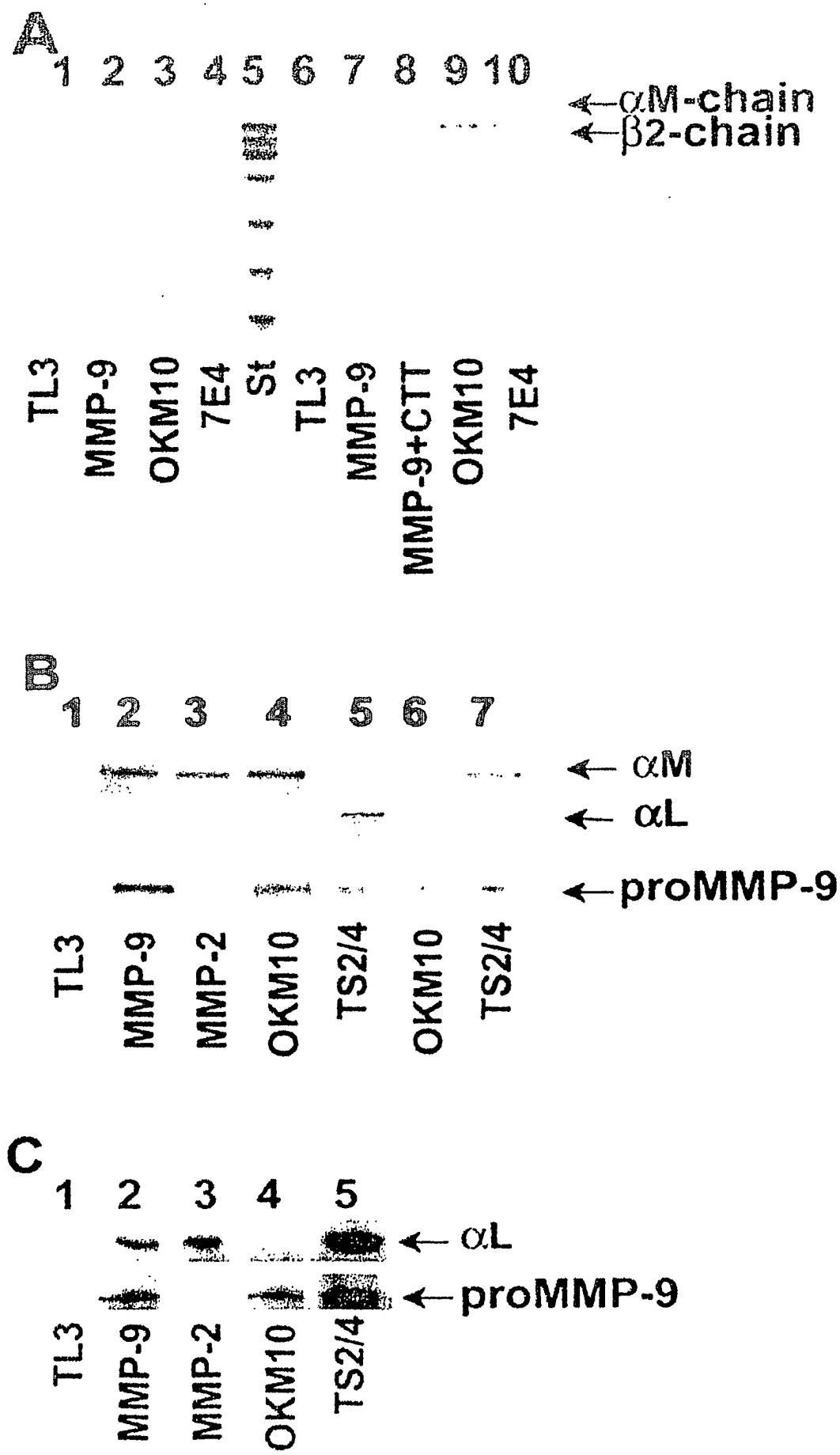


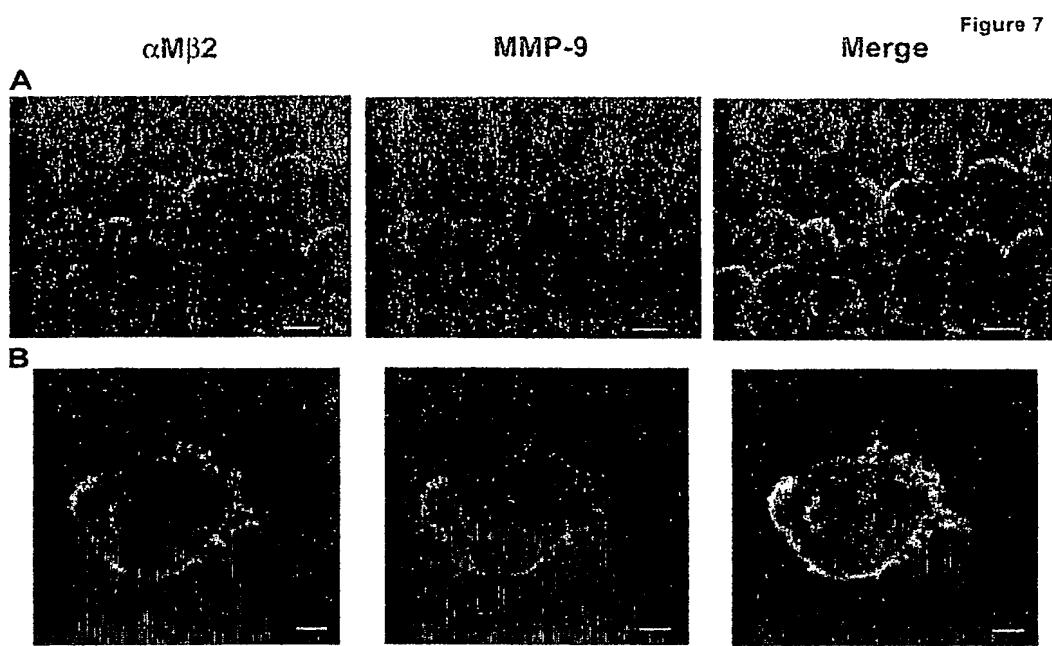
Figure 6

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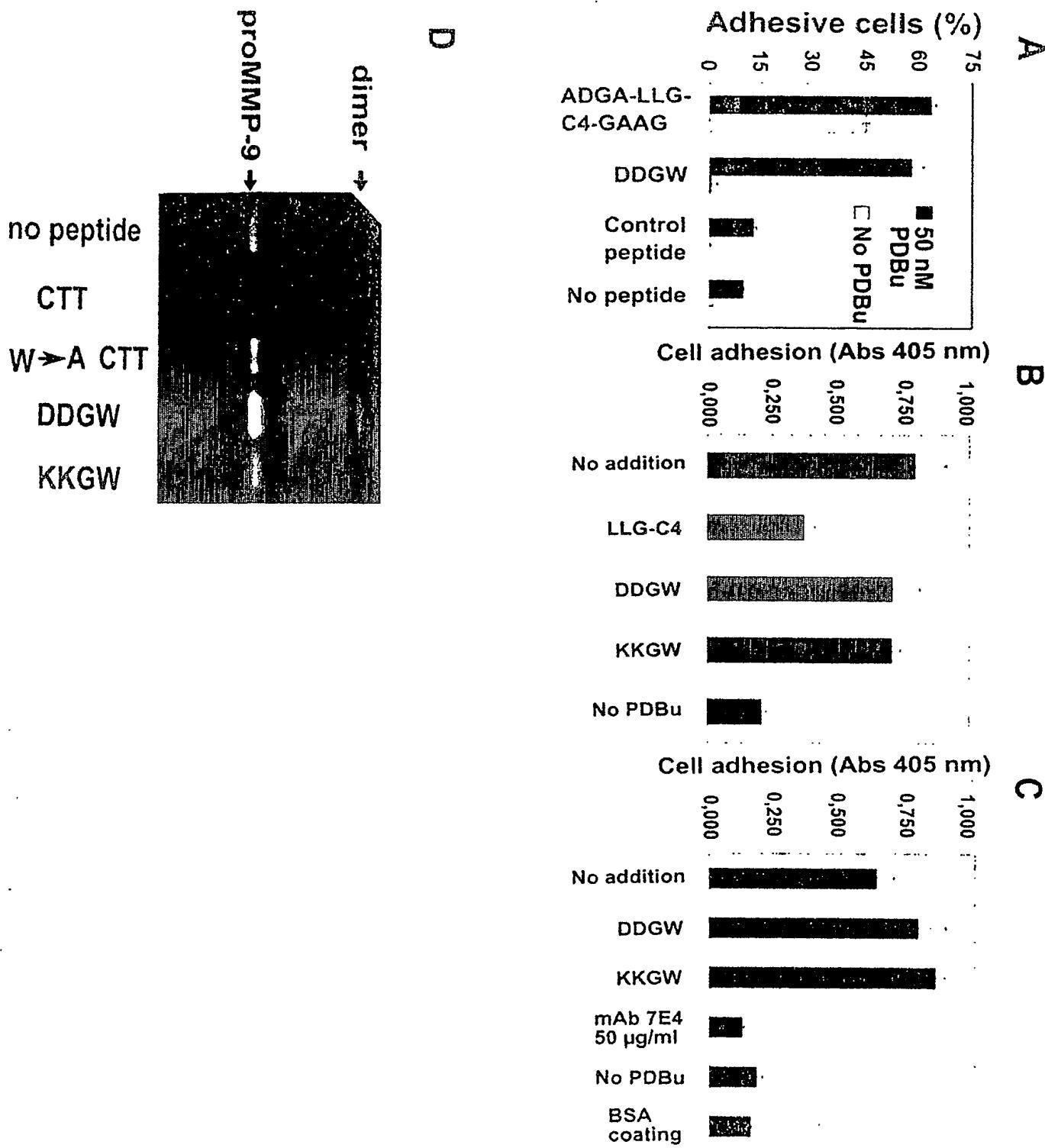
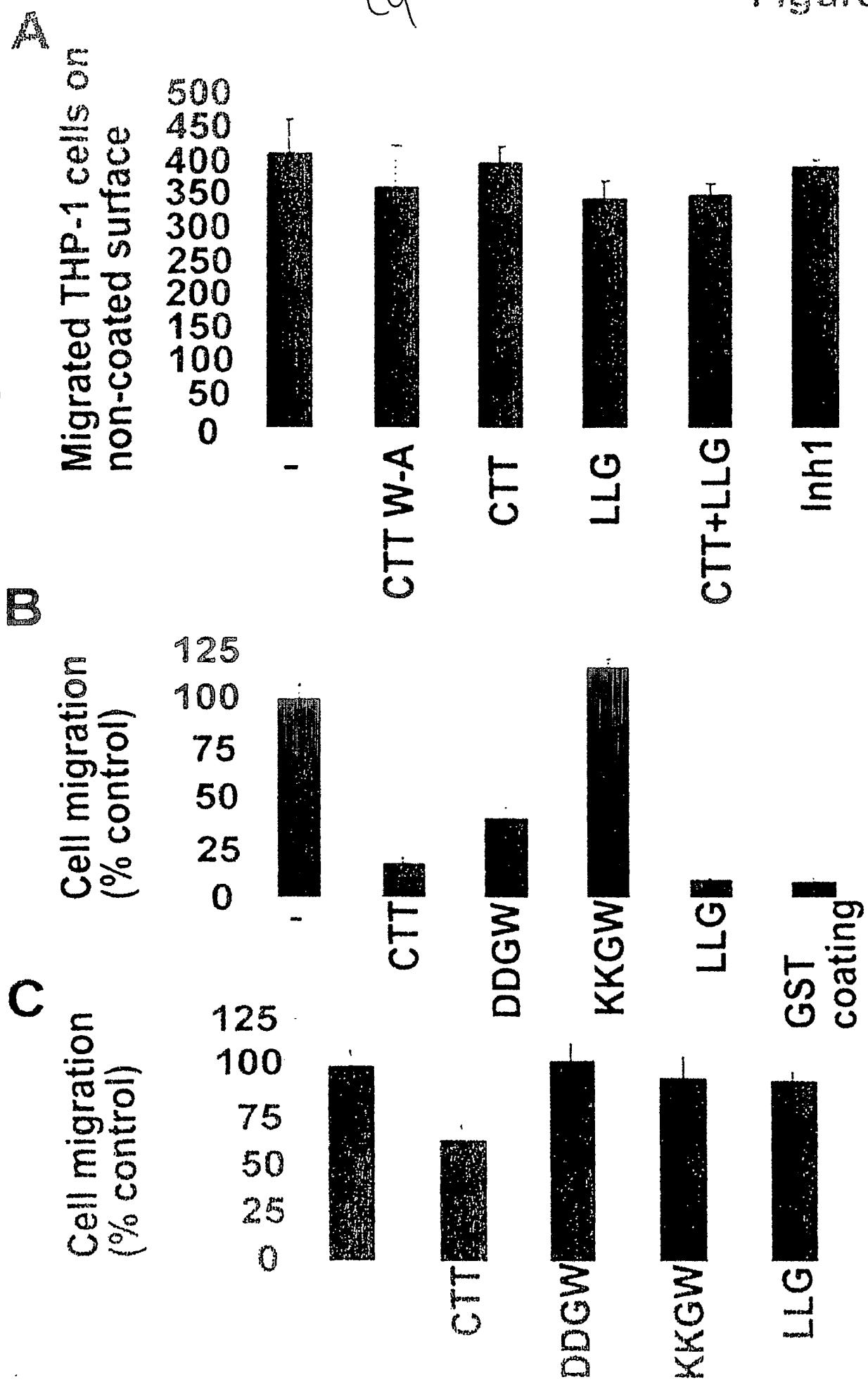


Figure 8

Figure 9

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